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SOME NOTES ON THE EFFECTS OF JET-EXIT DEISGN ON STATIC LONGITUDINAL STABILITY

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NACA

WASHINGTON

NACA LANGLEY MEMORIAL AERONAUTICAL LABORATORY

MEMORANDUM REPORT

for the

Air Materiel Command, Army Air Forces

and the

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MR No. L6D30a

SOME NOTES ON THE EFFECTS OF JET-EXIT DESIGN ON STATIC LONGITUDINAL STABILITY

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SUMMARY

A number of types of jet-exit designs have been tested, some in still air and some in moving air. The results, which have at least a qualitative generality, are presented herein. If the jet exit is improperly designed, the jet may suffer a deflection on leaving the nozzle. This may result in an unpredictable and erratic variation of stability and trim with speed.

It is shown that no deviation of the jet center line from its expected path is likely to be obtained if a jet exit is used that is normal to the flow. With a beveled exit appreciable deflections of the jet are possible when the Mach number at the jet exit attains or exceeds unity. At lower Mach numbers only a very small deviation of the jet is likely unless the internal fairing is unsymmetrical at the jet exit.

A fuselage or nacelle which projects over a discharging jet will probably not cause the jet to be deflected unless the natural expansion of the jet is restricted by the body. If the fairing between the wing and a jet or rocket unit suspended underneath is too blunt, the jet may be drawn toward the wing.

When the structure around the free jet behind the nozzle is not symmetrical with respect to the jet axis, the jet may adhere to the nearest surface causing a large and unpredictable effect on stability.

INTRODUCTION

The difficulties encountered in estimating the effects of power on the static longitudinal stability characteristics of the conventional propeller-driven aircraft have long been apparent. The recent advent of jet-propelled and rocket airplanes apparently served as a boon to the designer in that the power effect on stability was at first glance much more amenable to analysis. The methods for calculating the effects of jet operation on stability developed in references 1 and 2 have generally been shown to give good agreement with the results of wind-tunnel tests of several models for which the jet was simulated. The various effects, both direct and indirect, are discussed in reference 2 and formulas are derived for a quantitative evaluation in most instances.

An important part of the indirect effect of jet operation, the change in downwash at the tail, as well as the direct thrust moment are dependent upon the direction of the jet upon discharging from the exit. The geometric factors which may influence the position of the external jet are the exit shape and the geometry of any fuselage, nacelle, or fairing which is in proximity to the path of the external jet. The jet position may also be affected by internal asymmetry when the jet discharges within a body (as for a nozzle which does not extend to the rearmost portion of a fuselage). This paper presents the results of jet tests made in some cases in a wind tunnel (force measurements) and in other cases discharging into still air (total-head surveys) which show at least qualitatively the effects of the aforementioned geometric variables on jet deflection. In addition, because of its pertinency to the problem at hand and because of its otherwise limited circulation, some German data (reference 3) which show the effect of external fairing on jet spreading have been reproduced herein. It should be emphasized that the present report presents a compilation of the results of several investigations where most of the modifications were tested in connection with stability difficulties obtained on specific models. This report is therefore not an account of a complete or systematic investigation.

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COEFFICIENTS AND SYMBOLS

The coefficients and symbols used are defined as follows:

C_L lift coefficient (Lift/qS)

C_X longitudinal-force coefficient (X/qS)

C_m pitching-moment coefficient about center-of-gravity location shown in figure 1 (M/qSc')

T_c' effective thrust coefficient based on wing area (T_{eff}/qS)

ϕ angle of tilt of nozzle, degrees, positive downward, measured with respect to fuselage center line

Lift -Z

$\left.\begin{matrix} Z \\ X \end{matrix}\right\}$ forces along axes, pounds

M Mach number; also moment about Y axis, pound-feet

M_e Mach number at jet exit

M_s Mach number at survey plane

T_{eff} jet effective thrust, pounds

H total head, pounds per square foot

q free-stream dynamic pressure, pounds per square foot ($\rho V^2/2$)

S wing area (10.4 sq ft on model)

c' wing mean aerodynamic chord (M.A.C.) (1.48 ft on model)

V free-stream velocity, feet per second

V_j jet velocity at nozzle, feet per second

ρ mass density of air, slugs per cubic feet

α angle of attack of fuselage center line, degrees

h distance between the center of gravity and the fuselage center line (0.0183 ft on model); positive when center of gravity is above fuselage center line

l distance from the center of gravity to the point about which the thrust line pivoted (approx. 4.0 ft on model); positive rearward

D jet-exit diameter

d distance from jet exit to survey plane

APPARATUS AND METHOD

Description of Models and Apparatus

Still air.- A circular nozzle with an exit shape normal to the flow (hereafter referred to as the normal exit), a nozzle with a beveled exit, and a nozzle with an asymmetric internal shape were tested with a high-speed cold jet exhausting into still air. (See fig. 2.) In addition, a streamlined body was placed over the normal jet exit to approximate roughly the fuselage of an airplane and tests were made with and without a fairing of modeling clay. (See fig. 3.) The conventional rake of low-speed total- and static-pressure orifices was used for all pressure surveys made. It should therefore be noted that for the highest jet speeds the pressure readings and hence also the computed Mach numbers may be slightly in error. The air supply was obtained by running a line to a reservoir of compressed air. A schematic sketch of the test setup is shown in figure 4. Because the cold jet of these tests would not reproduce conditions on an airplane, the results were considered to have only qualitative application. Static pressures at the nozzle exit and total head in the pipe were measured. (See fig. 4.) The Mach numbers at the jet exit were computed from these data.

Göttingen.- The German data, a portion of which is reproduced herein, were obtained in the Göttingen No. 2 wind tunnel. A sketch showing some of the details of the model and fairing is given in figure 5. A circular fuselage with a slight taper was used. The nozzle was also circular with a large conical plug in the center.

This arrangement was tested with the fuselage placed so that a distance equal to the nozzle exit diameter separated the lower surface of the nozzle exit and the tunnel floor. Two fairings that ended under the nozzle exit were used between the fuselage and the tunnel floor. One of the fairings (fairing A) terminated in a bluff shape with a width equal to the jet-exit diameter; the other (fairing B) had a more streamlined appearance tapering to a knife edge at the exit.

Langley 7- by 10-foot tunnel.- Tests to determine the effects of variation in nozzle geometry for a specific wing-fuselage combination were made. Thrust was obtained through the use of a two-stage axial-flow blower which was driven by two 27-horsepower electric motors. The speed was determined with an electric tachometer. A drawing of the model setup used for these tests is shown in figure 6. The original nozzle, which was supplied with the model, was unsymmetrical and diverging as shown in figure 7. A modified nozzle (fig. 8) had an exit which was normal to the jet. Both of these nozzles were set parallel to the fuselage center line at station A (fig. 1). In addition, data were obtained with tilted extensions to the modified exit (4°) or with the entire tail-pipe assembly tilted 4° from the fuselage break line indicated in figure 9. In some of the tests where the entire assembly was tilted the extension to the nozzle remained attached (set at 0° relative to the tail pipe) while in others it was removed.

Methods

Still air.- Total- and static-pressure surveys were made at distances of 8 and 12 nozzle diameters behind the nozzle exit. The jet velocity was varied by throttling a line running to the reservoir of compressed air. The approximate Mach number at the jet exit varied from 0.65 to supersonic and that near the jet center line in the survey plane varied from 0.37 to 0.96.

Göttingen.- Total- and static-pressure surveys were made at a number of axial distances behind the jet exit. The tests were made in still air and at two tunnel speeds. The tunnel velocity for the data reproduced herein corresponded to a Mach number of about 0.10 and the velocity of the jet at the exit corresponded to a Mach number of about 0.20.

Langley 7- by 10-foot tunnel.- The tests were made at tunnel speeds corresponding to Mach numbers of about 0.053 to 0.079 with the jet velocity at the exit ranging up to a Mach number of about 0.3. All tests were made by measuring the longitudinal force and pitching moment for a range of blower speeds with the model at 0° angle of attack. Thrust coefficients were determined from the relation

$$T_c' = C_{X_{\text{blower on}}} - C_{X_{\text{blower off}}}$$

where $C_{X_{\text{blower on}}}$ is the longitudinal-force coefficient of the model with the blower operating and $C_{X_{\text{blower off}}}$ is the longitudinal-force coefficient of the model with a fairing placed over the duct inlet to prevent air flow through the duct. For a given blower speed this definition of thrust coefficient is believed to result in a slightly higher evaluation due to an excessive blower-off drag. A more accurate value of blower-off drag would have been obtained if a streamlined fairing were placed over the tail cone or if it had been possible to obtain a jet-exit velocity equal to that of the free stream.

RESULTS AND DISCUSSION

The results of the total-head surveys made in still air which show the respective effects of normal, beveled, and unsymmetrical exit shapes on jet deflection are presented in figure 10. The unsymmetrical nozzle configuration (fig. 2(c)) was chosen to approximate the original installation tested on the wind-tunnel model (fig. 7). Preliminary tests on the wind-tunnel model had indicated an erratic variation of C_m with T_c' with this nozzle which was completely rectified when a modified nozzle (normal exit shape, fig. 8) was used.

The results of total-head surveys made in still air to show the effect of the fuselage projecting over a normal exit are given in figure 11. The German data (velocity profiles behind a jet obtained from wind-tunnel tests) illustrate the effects of variation in fairing immediately forward of the jet on the behavior of the jet in close proximity to a two-dimensional surface. (See fig. 12.)

The effects of internal asymmetry on jet deflection are shown in figures 13 and 14. This asymmetry was brought about while attempting to improve the longitudinal stability characteristics of a proposed jet-propelled fighter. (The wing-fuselage combination is shown in fig. 6.) It was understood that on the full-scale airplane the jet would be tilted by tilting the jet nozzle inside the tail pipe, leaving the position of the tail pipe unchanged. On the model this was represented by tilting extensions to the nozzle 4° (fig. 9). The internal asymmetry near the exit was eliminated for tests where the jet was tilted by rotating the entire tail pipe assembly behind the break line 4° above pivot B.

Effect of Exit Shape

For the normal exit the jet center line remained unaltered upon leaving the nozzle. (See fig. 10(a).)

With the beveled exit no deflection is shown until supersonic velocities are obtained at the exit. Then deflections of the order of 4° or 5° occur. (See fig. 10(b).) The absence of any appreciable jet deflections with a beveled exit at subsonic speeds has also been shown from the results of another investigation (unpublished). In addition the phenomenon of jet deflection has been observed in tests in which air or steam was discharged at supersonic velocities from diverging and parallel wall pipes with beveled exits. The results of these tests, together with a discussion of some of the theoretical aspects of the problem, may be found in reference 4 (pp. 118-156). It is shown that the amount of jet deflection is critically dependent upon the relation of the back pressure to the pressure in the nozzle. The deflection is dependent to a much lesser degree on the frictional force in the beveled portion of the nozzle.

On all present turbojet airplanes the jet velocities are entirely subsonic. The temperature gradients of an actual airplane jet were not reproduced in the present tests, however, or in the unpublished tests referred to earlier. It is therefore not entirely safe to conclude from the negative results of these tests for subsonic exit velocity that an actual jet airplane will not show harmful effects from beveling the jet exit. Also, the positive results of the present tests for supersonic velocity are directly applicable to rocket-powered airplanes. Beveling the rocket nozzle would be expected to introduce considerable jet deflection and variation of deflection with flight condition.

For the unsymmetrical nozzle it may be noted that at the lowest speed tested, $M_e = 0.70$ (fig. 10(c)), a large upward deflection was obtained. This deflection was probably caused by the flow separating from the lower surface of the nozzle but following the contour of the upper surface. For the higher jet velocities the magnitude of this trend appears to be much reduced (compare figs. 10(b) and 10(c)) and it is a matter of conjecture whether the separation is a Reynolds number or a Mach number effect. The unsymmetrical nozzle is clearly to be avoided in the design of jet airplanes.

Effect of External Body or Fairing

No noticeable jet displacement is indicated for the limited jet-fuselage combinations of the present investigation either with or without the modeling clay fairing. (See fig. 11.) This substantially agrees with the results of another very limited investigation (unpublished data) in which the jet also discharged under a fuselage. British data (reference 5) seem to indicate that the jet path will not be materially affected by being in proximity to a body if the body does not lie in the natural path of spreading of the jet (the angle of spreading may be obtained by using methods given in references 1 and 2)[1]. When the body does lie in the path of the jet, the jet may be deflected through large angles. This is known as the Coanda effect and is discussed in some detail in reference 5.

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[1]Figure 3 shows that the fuselage tested in still air would be in the path of the jet for a spreading angle of more than 10°. Calculations based on the test data (fig. 10) indicated an actual spreading angle of 8° or 9° as compared to a computed value of about 13° (reference 2). The difference is probably caused by the difference in the shape of the velocity profile. The edge of a jet is ill-defined in any case and the important consideration is that the fuselage lie outside the region of appreciable jet velocity. An estimate of this region can be obtained from reference 2.

It is apparent from the German data (fig. 12) that the jet was not drawn toward the tunnel wall when the streamlined fairing (fairing B) was used. In fact the jet seems to be tilted slightly away from the wall. However, when the bluff fairing (fairing A) was tested the jet was drawn toward the tunnel wall, probably because the entrainment of air into the jet was restrained somewhat by the fairing. A problem of this type might be encountered in designing a fairing for a jet or rocket unit located under a wing. The data of figure 12 is representative of a unit located at about a mid-chord position.

Effect of Internal Asymmetry

It can be shown theoretically that, for small jet deflections ($\cos \phi \approx 1$), the value of $(\partial C_m/\partial T_c')$[1] may be obtained from

$$\frac{\partial C_m}{\partial T_c'} = \frac{h}{c'} - \frac{\frac{l}{c'} \sin \phi}{1 - \frac{1}{2\left(\frac{V_j}{V}\right)}}$$

where the symbols have been previously defined. (See also fig. 1.)

Computations with the above equation were made using the theoretical variation of V_j/V with T_c' for a cold jet having a density equal to that of the free stream. The effect of turning the inlet air is not included in the equation. Inasmuch as all test data presented were obtained at $\alpha = 0^\circ$ and near zero lift (negligible wing

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[1]The increment to the stability of the complete model contributed by the direct thrust force, $\Delta(\partial C_m/\partial C_L)$, is $\frac{\partial C_m}{\partial T_c'} \times \frac{\partial T_c'}{\partial C_L}$. For this model a change in $\partial C_m/\partial T_c'$ of 0.037 was equivalent to a 1-percent M.A.C. shift in neutral-point location on the airplane for the full-power condition.

upwash at the inlet) the equation should be valid for comparison. The results of calculations for a jet deflection, $\phi = 4^{\circ}$, are shown in figure 14.

A comparison of the theoretical $\partial C_m/\partial T_c'$ and experimental values with the shorter tilted nozzle extension (fig. 14, q = 4.09 lb/sq ft) shows the experimental values to be considerably more negative. It is believed that inclination of the jet by means of a nozzle extension that does not extend to the end of the tail pipe causes the jet to be drawn toward the wall of the tail pipe nearest the nozzle exit. Thus in this instance the jet is actually inclined a larger amount than the geometry of the system would indicate. There is also a break in the curve of C_m against T_c' in the higher thrust range. (See fig. 13.) Check tests indicated the likelihood of two alternative flow regimes in this region.

When the entire tail-pipe assembly behind the fuselage break line (including the shorter extension) was tilted 4° the values of $\partial C_m/\partial T_c'$ agreed reasonably well with the theoretical, indicating that the jet was being inclined as desired. With the extension removed, however, the data appeared more erratic and were farther from the theoretical over part of the thrust range. (See fig. 14.) The tests with the nozzle extension lengthened until it coincided with the end of the tail pipe were intended to provide a further check on the effect of nozzle length on jet inclination. The test points are somewhat scattered (fig. 13) possibly because of a failure to obtain a smooth juncture between the short extension and the lengthened extension. The data do indicate, however, that the variation of C_m with T_c' with the lengthened extension was considerably closer to the results obtained with the other means of jet tilt than with the shorter nozzle extension tilted.

Applicability

Throughout most of this paper the effects of various jet-exit designs on the static longitudinal stability and trim characteristics have been stressed. It is possible, however, that some of these difficulties could also be obtained on the static directional stability and trim characteristics.

Limitations.- Because of problems posed by limitations in testing techniques, actual conditions obtained on an airplane could not be reproduced. Although a cold jet was used throughout, the results of tests with supersonic jet velocities reported in reference 4 show the same effects of a beveled exit on jet deflection when a hot jet is used. On some jet airplanes a ring of cooling air surrounds the internal hot jet. The influence of this arrangement on the results presented in this paper is not known. The deflections obtained from the still air tests are probably somewhat larger (for a constant jet velocity) than would have been indicated if the data had been obtained in moving air.

CONCLUDING REMARKS

It is shown that no deviation of the jet center line from its expected path is likely to be obtained if a jet exit is used that is normal to the flow. With a beveled exit appreciable deflections of the jet are possible when the Mach number at the jet exit attains or exceeds unity. At lower Mach numbers only a very small deviation of the jet is likely unless the internal fairing is unsymmetrical at the jet exit.

A fuselage or nacelle which projects over a discharging jet will probably not cause the jet to be deflected unless the natural spreading of the jet is restricted by the body. If the fairing between the wing and a jet or rocket unit suspended underneath is too blunt the jet may be drawn toward the wing.

If the structure around the free jet behind the nozzle is not symmetrical with respect to the jet axis, the jet may adhere to the nearest surface causing a large and unpredictable effect on stability.

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5. Squire, H. B., Harper, D. J., Bekassy, J., and Chester, W.: Wind Tunnel Tests of Oblique Jet Units. Rep. No. Aero 2007, British R.A.E., Jan. 1945.

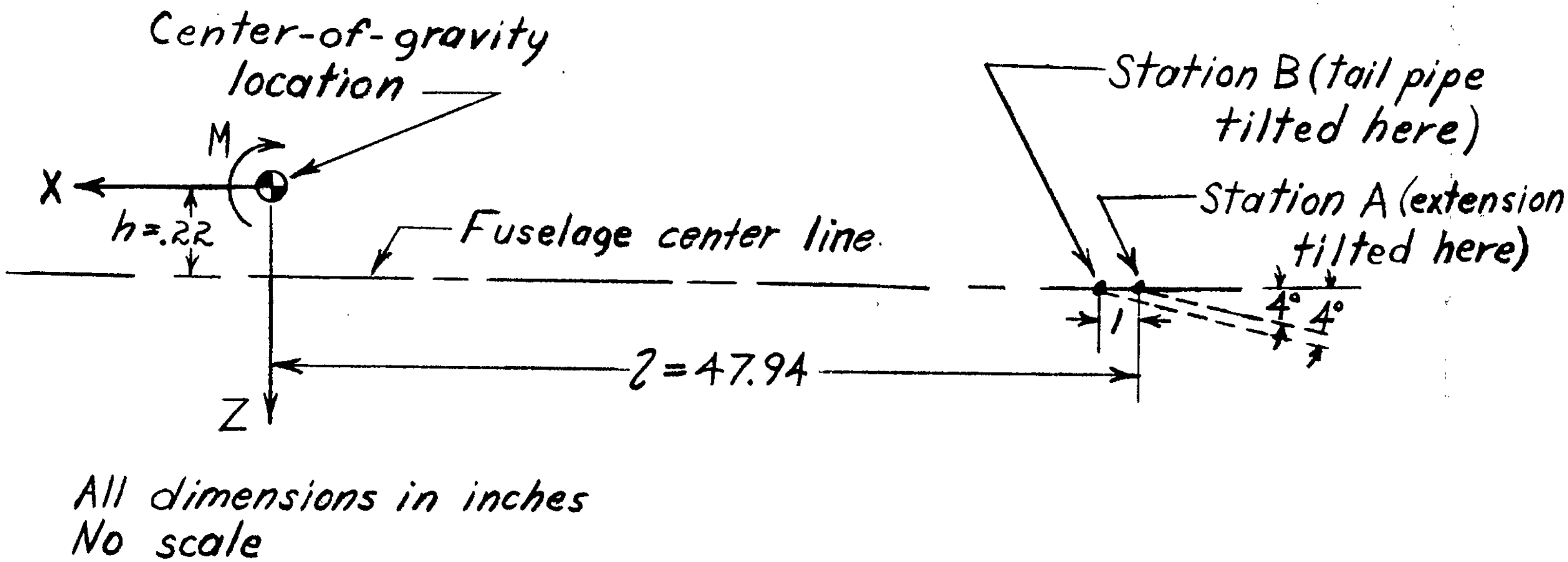

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Figure 1.- Schematic sketch showing relation of center of gravity and stations at which jet nozzle was tilted for 1/5-scale model of a jet airplane. Wind tunnel tests.

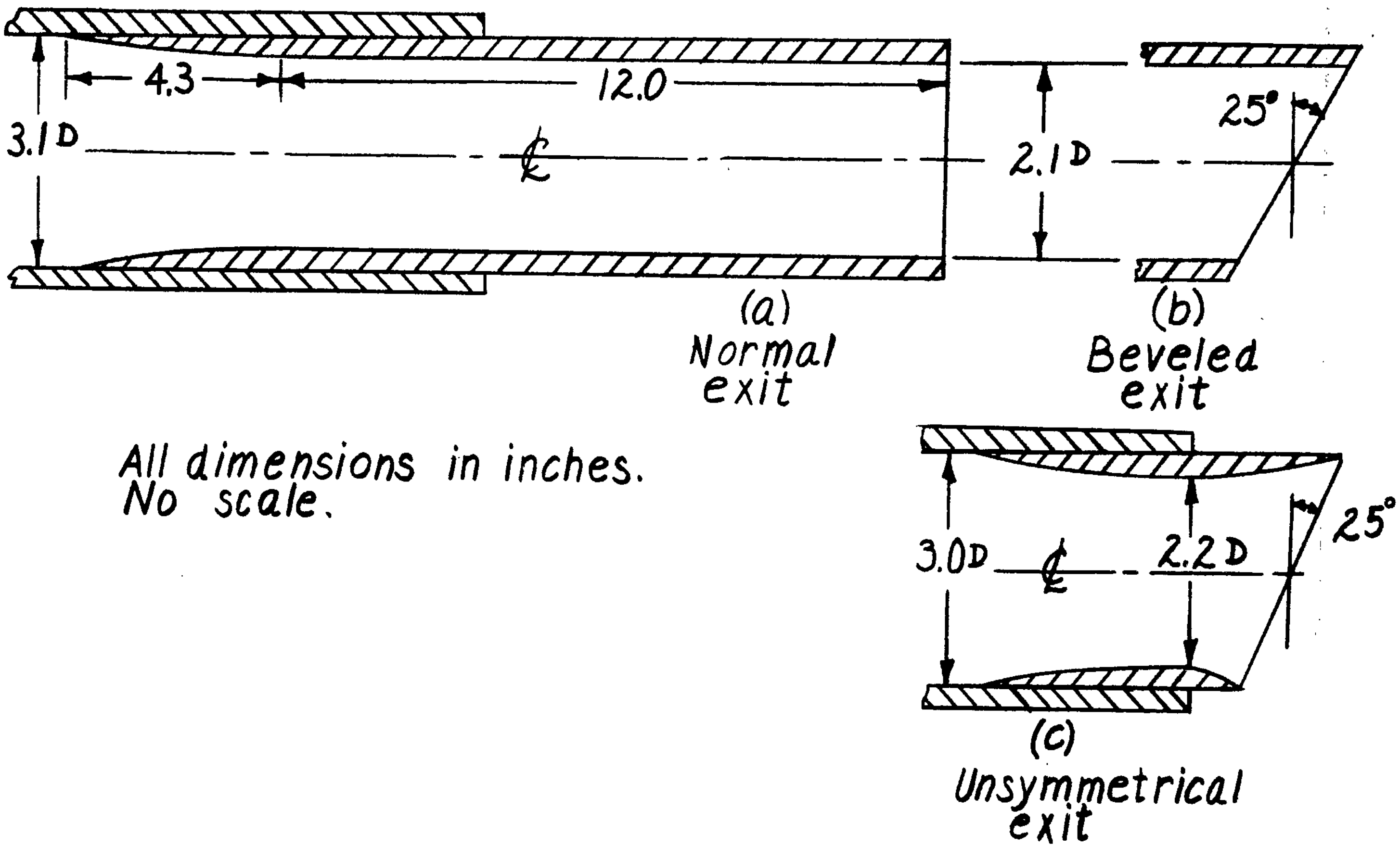

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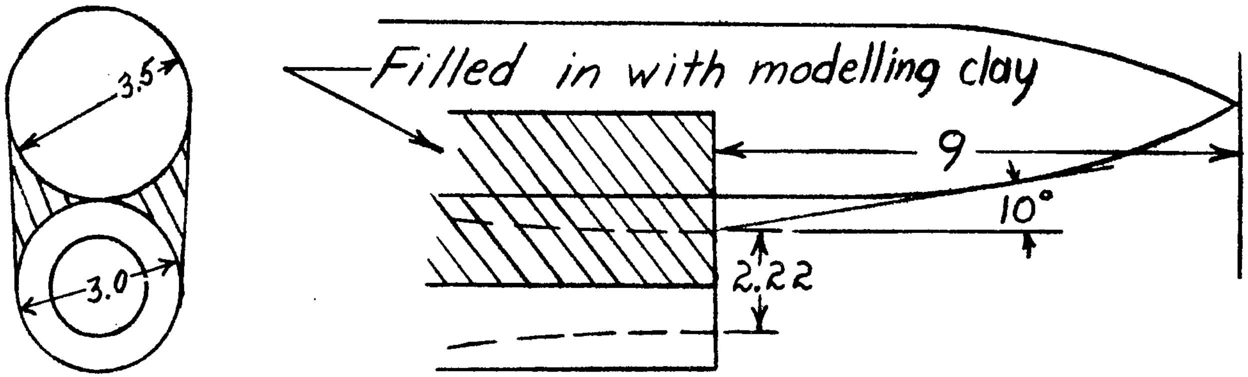
Figure 2.- Details of nozzles used to determine the effect of exit bevel on jet inclination. Tests in still air.



All dimensions in inches

No scale

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Figure 3.- Schematic sketch showing set-up used to simulate a jet discharging under a fuselage. Tests in still air.

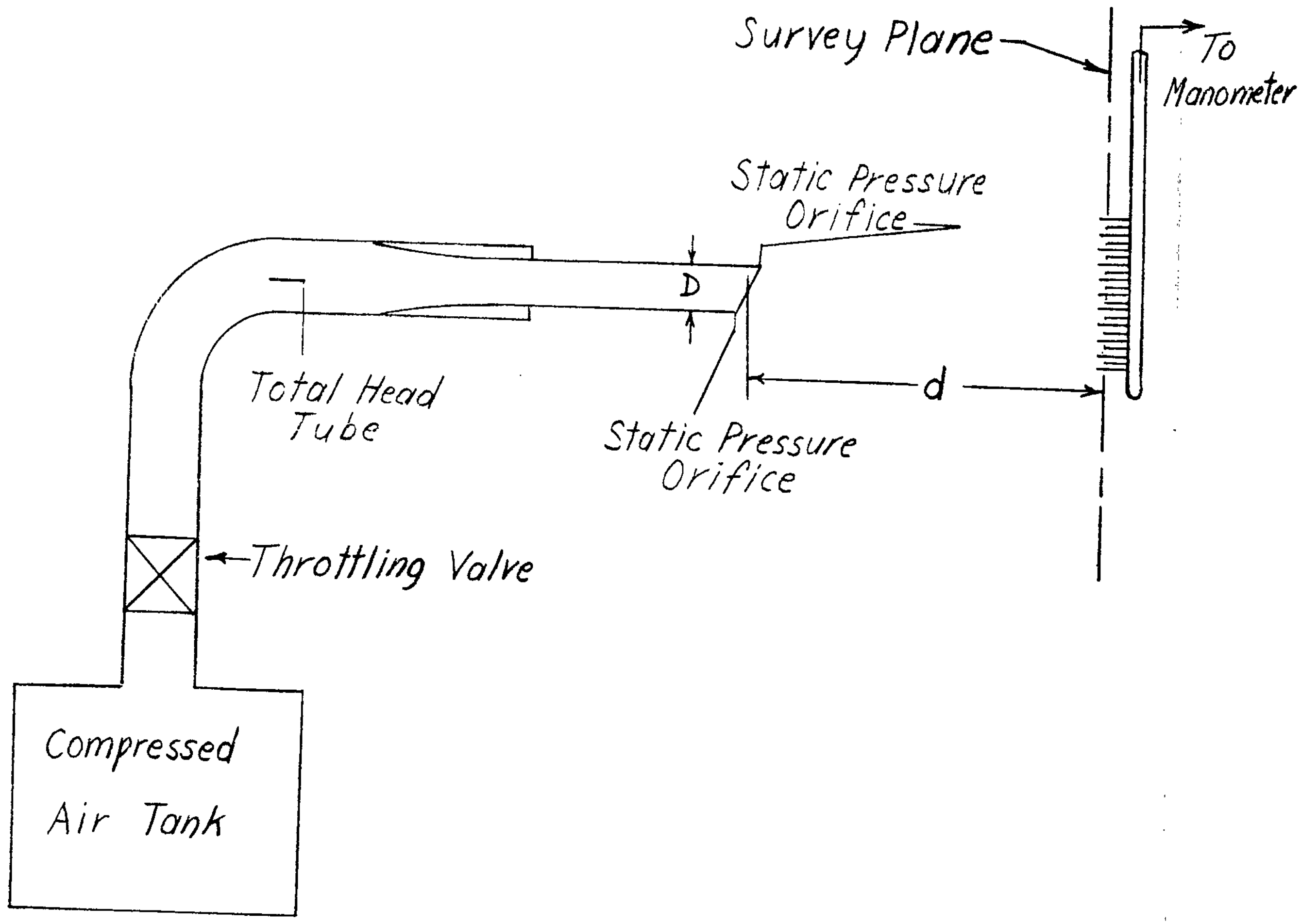

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Figure 4.- Schematic sketch of test set-up used for still-air surveys.

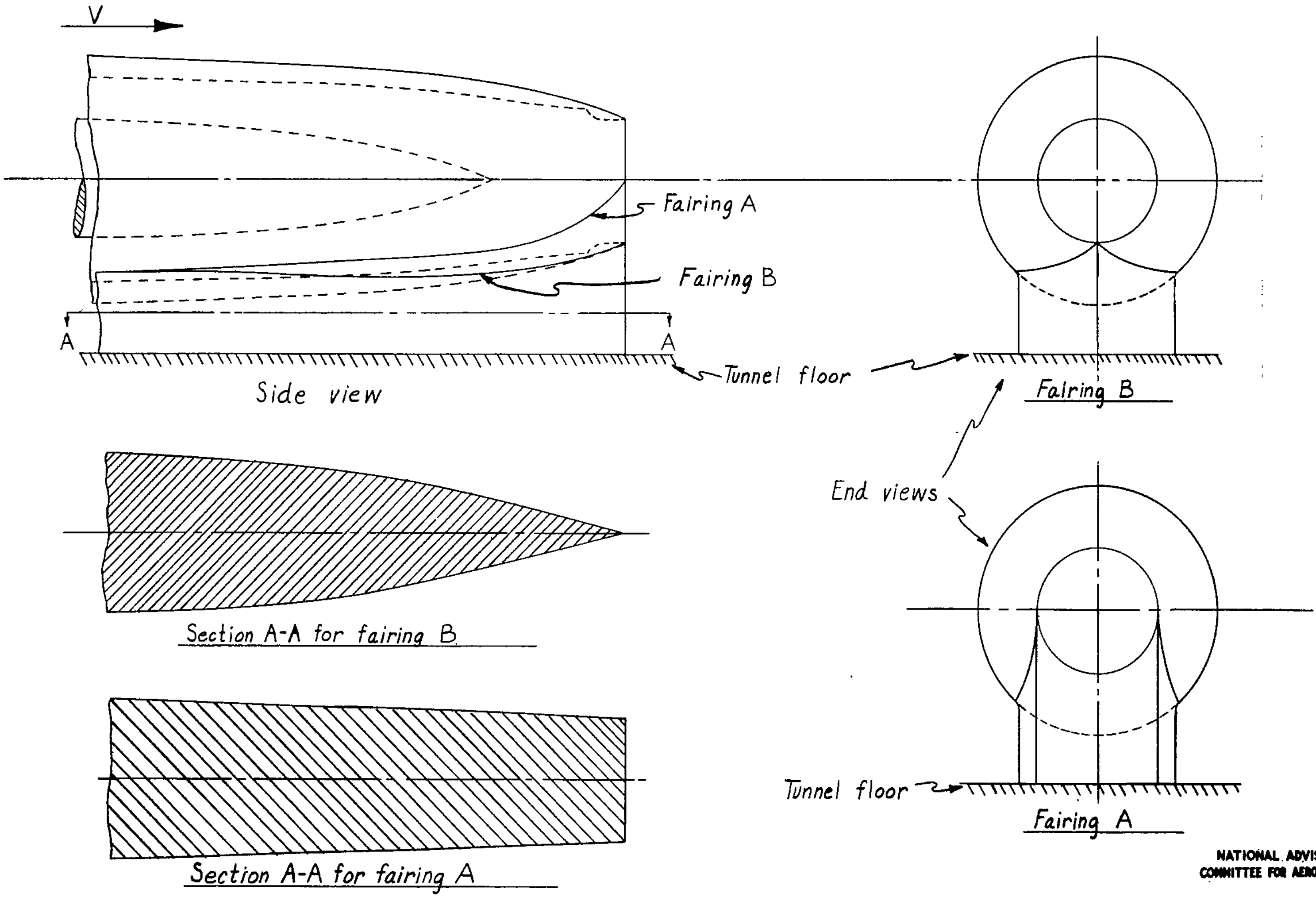

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Figure 5.- Sketch showing details of fuselage-tunnel wall fairings tested at Göttingen (reference 3).

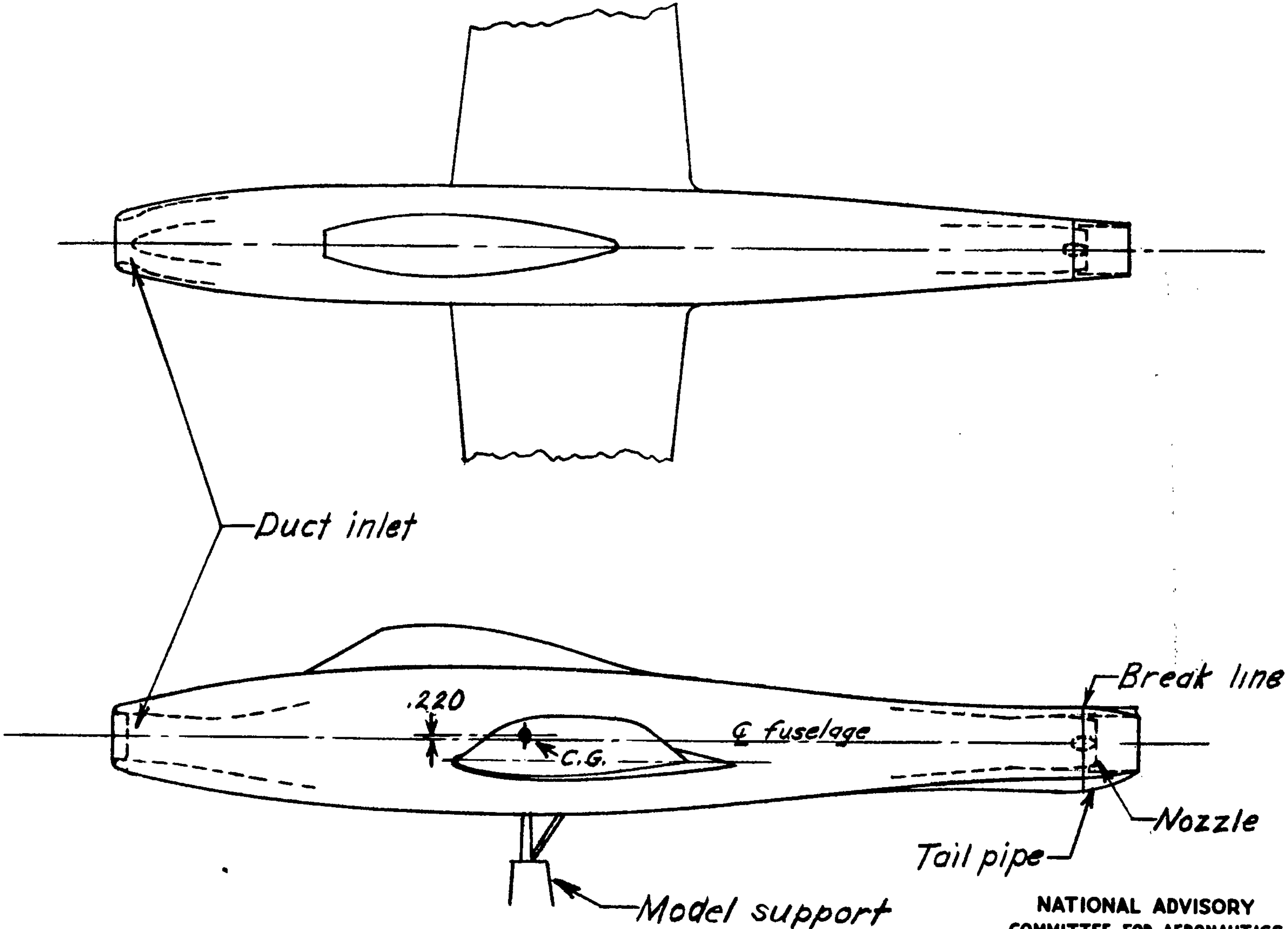

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Figure 6.-Model used for tests in 7-by 10-foot tunnel.

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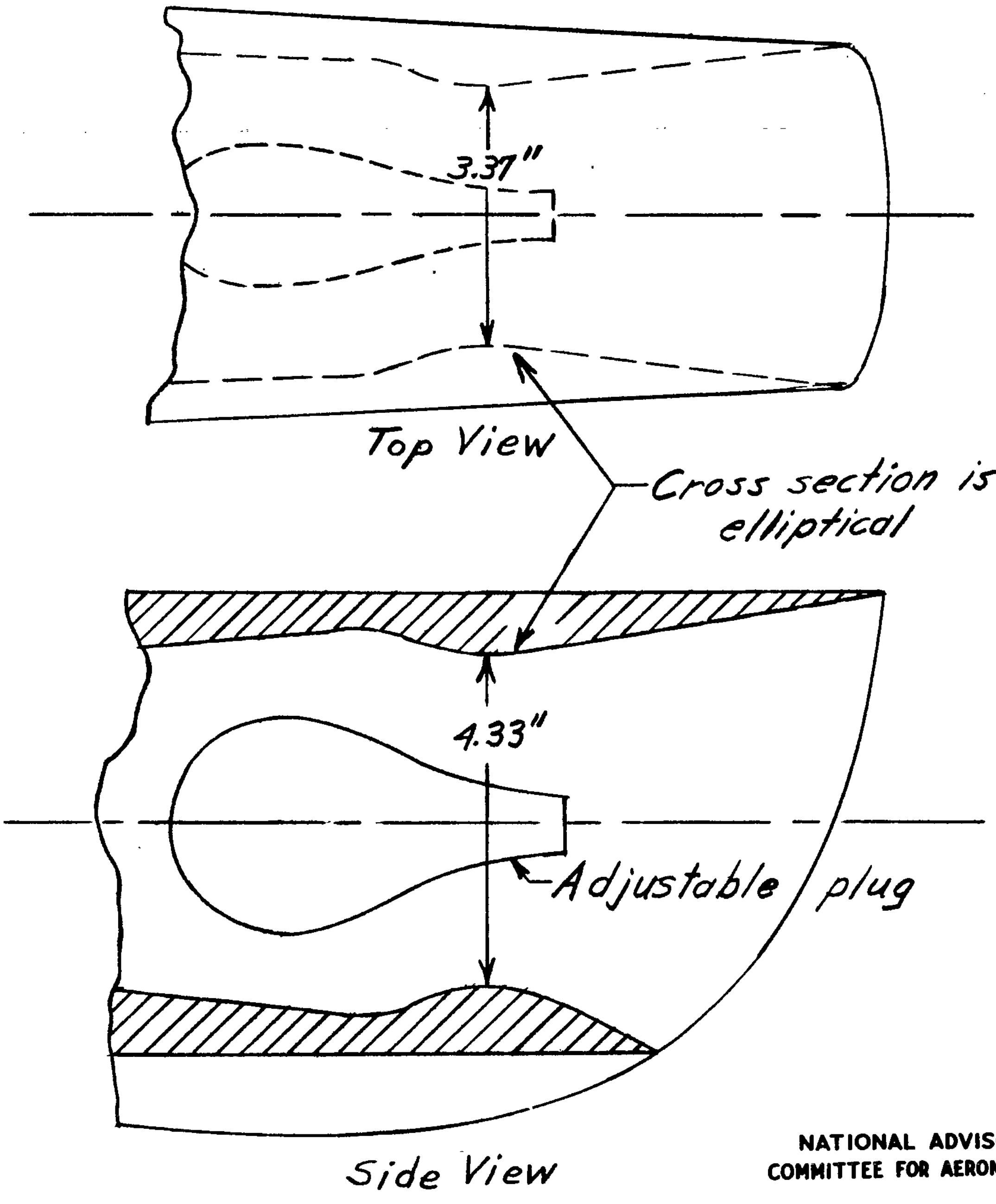

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Figure 7.- Original nozzle on complete wind-tunnel model.

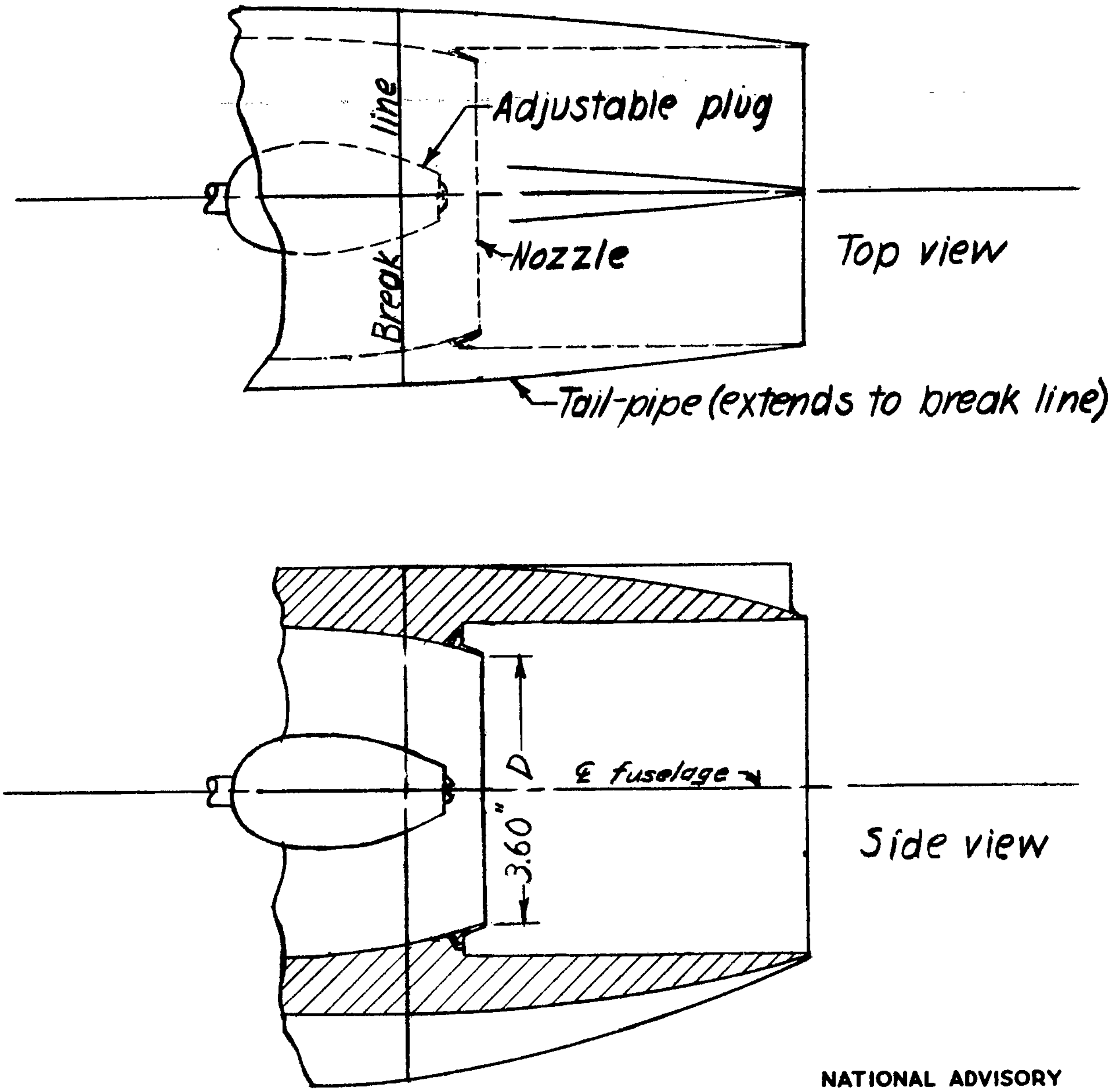

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Figure 8.- Modified nozzle and tail pipe tested on complete wind-tunnel model.

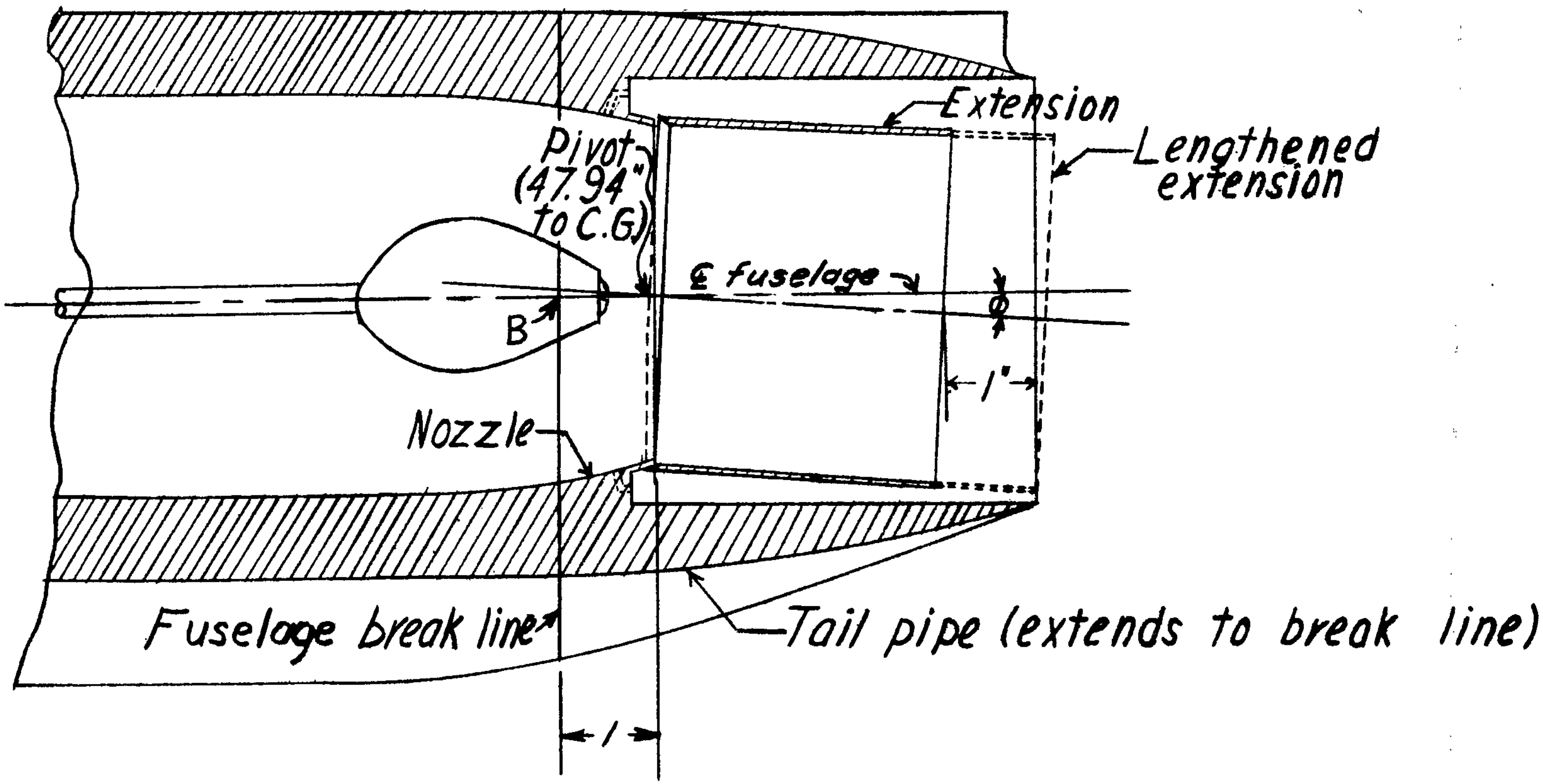

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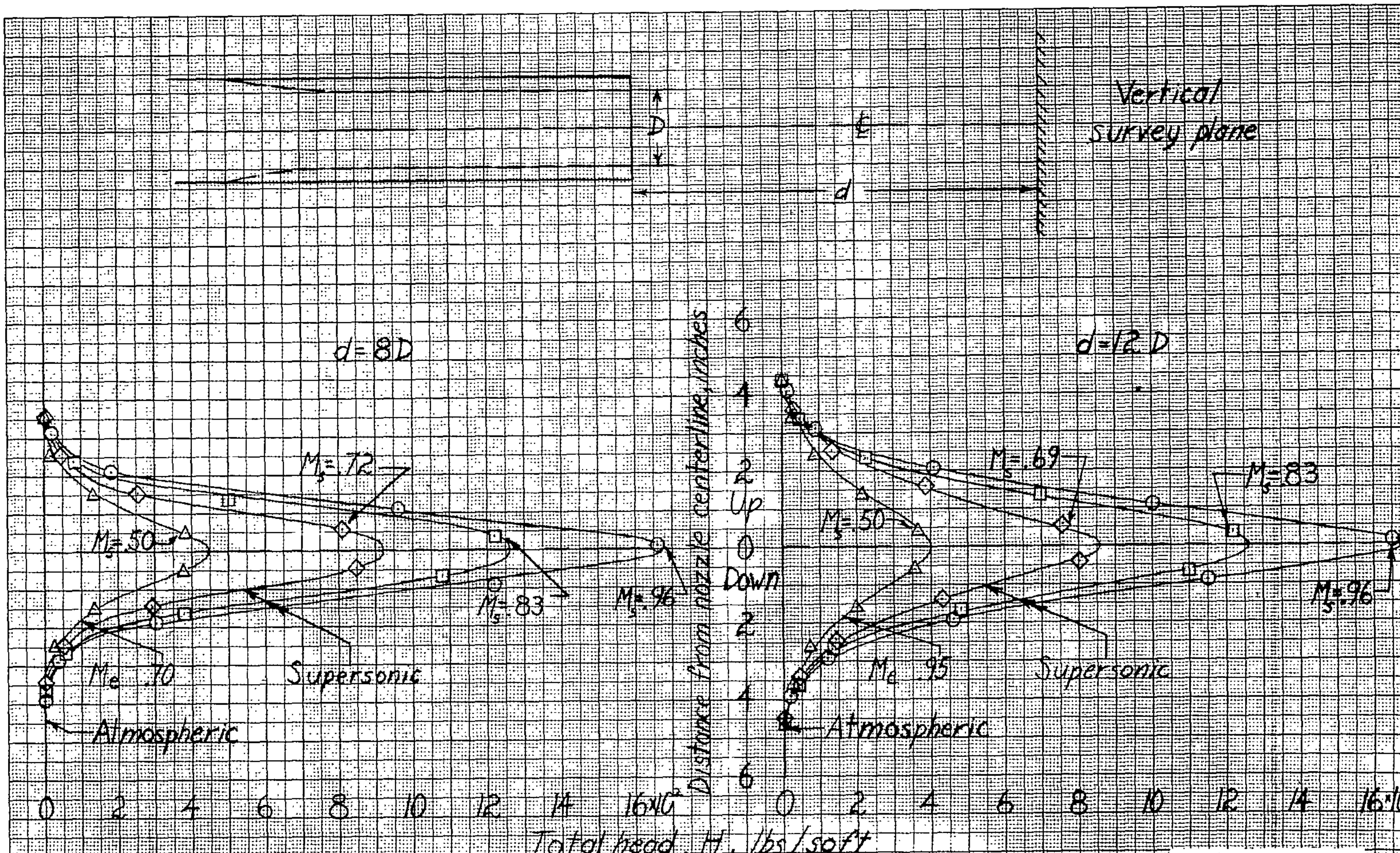
Figure 9.- Modified nozzle with extensions for deflecting jet. Wind-tunnel model.



(a) Normal nozzle exit

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Figure 10.- Total head surveys for determination of the effect of nozzle configuration on jet inclination. Tests in still air.

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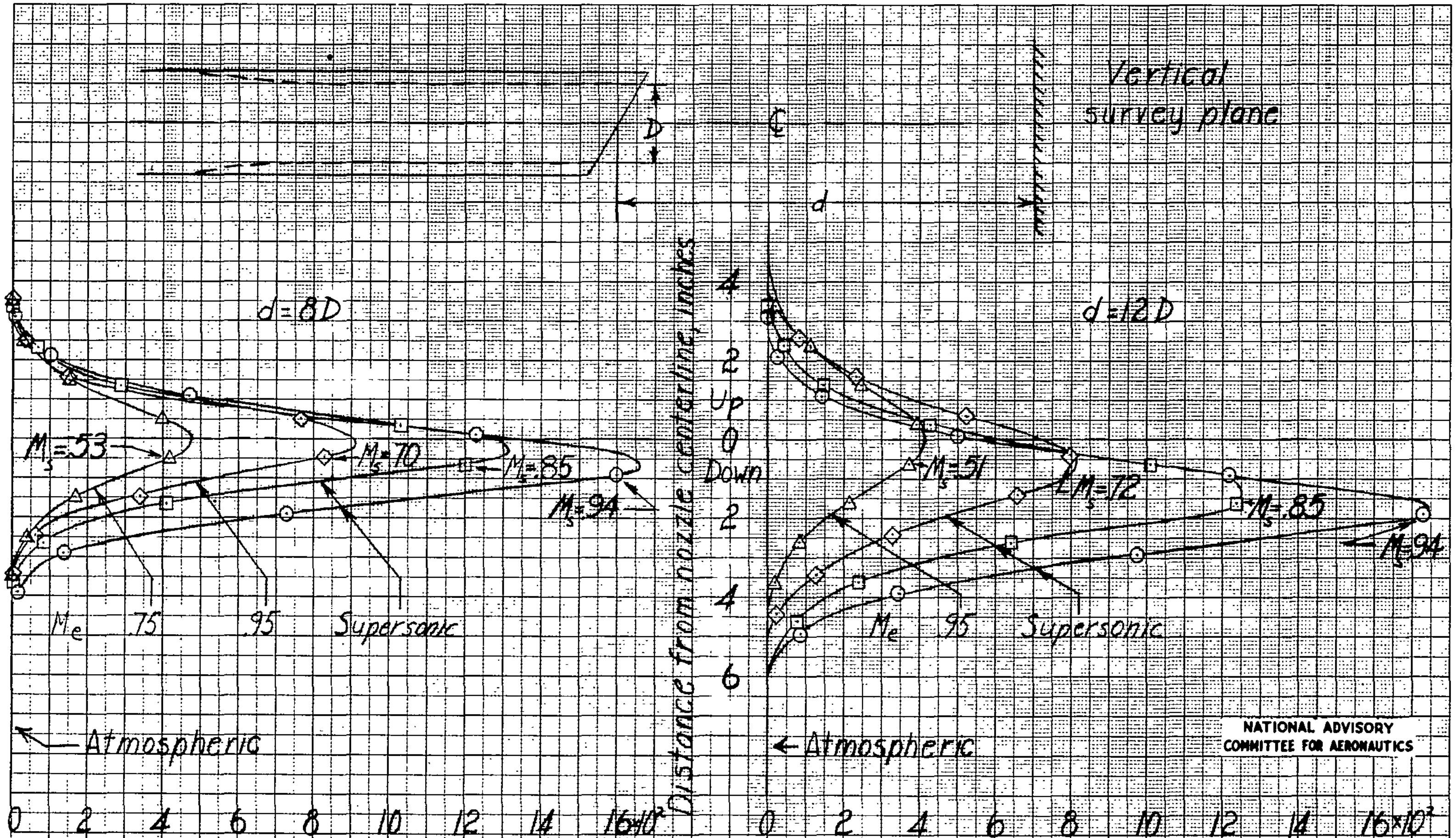

Total head, H, lbs/sq ft

(b) Beveled nozzle exit

Figure 10.- Continued

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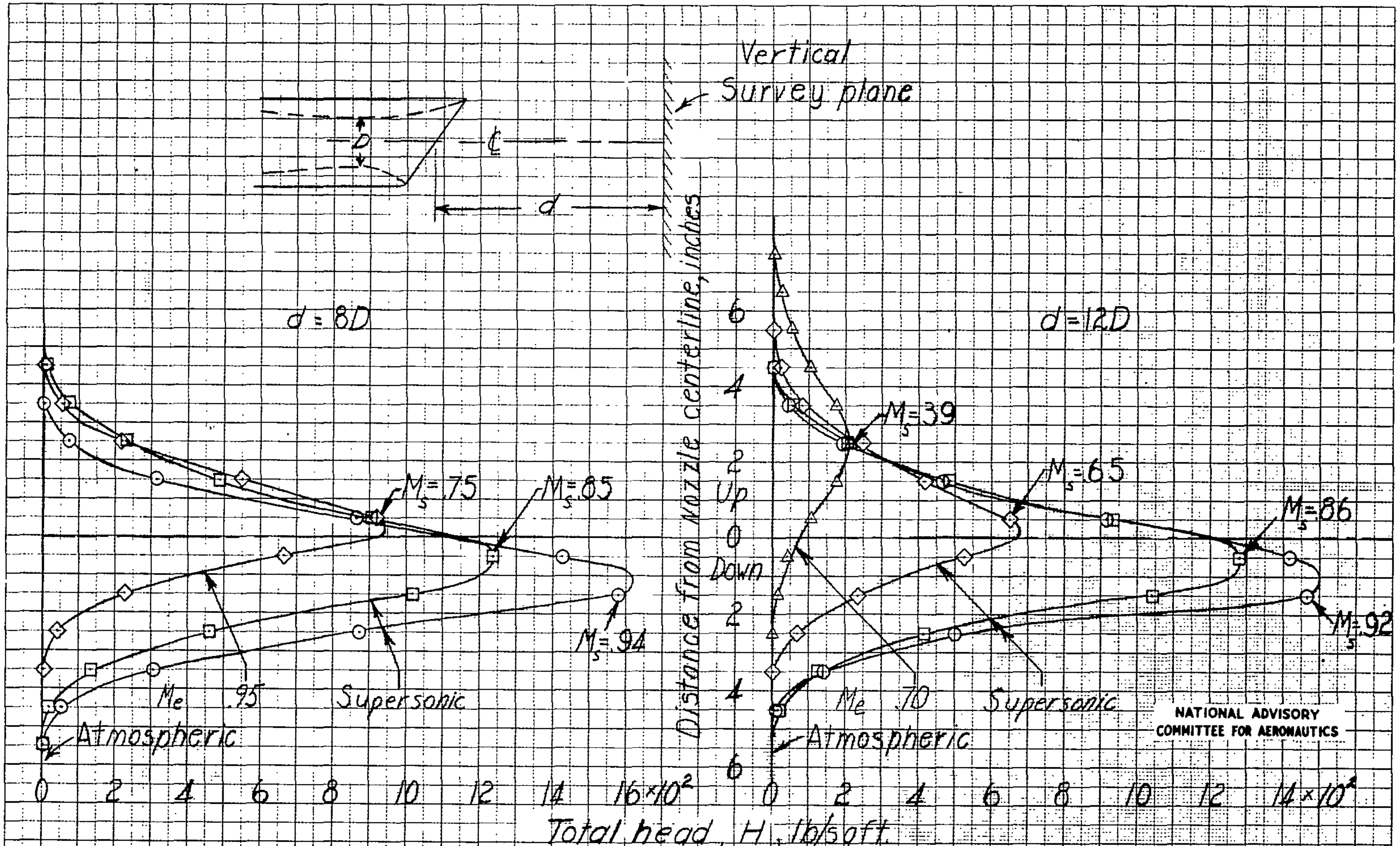
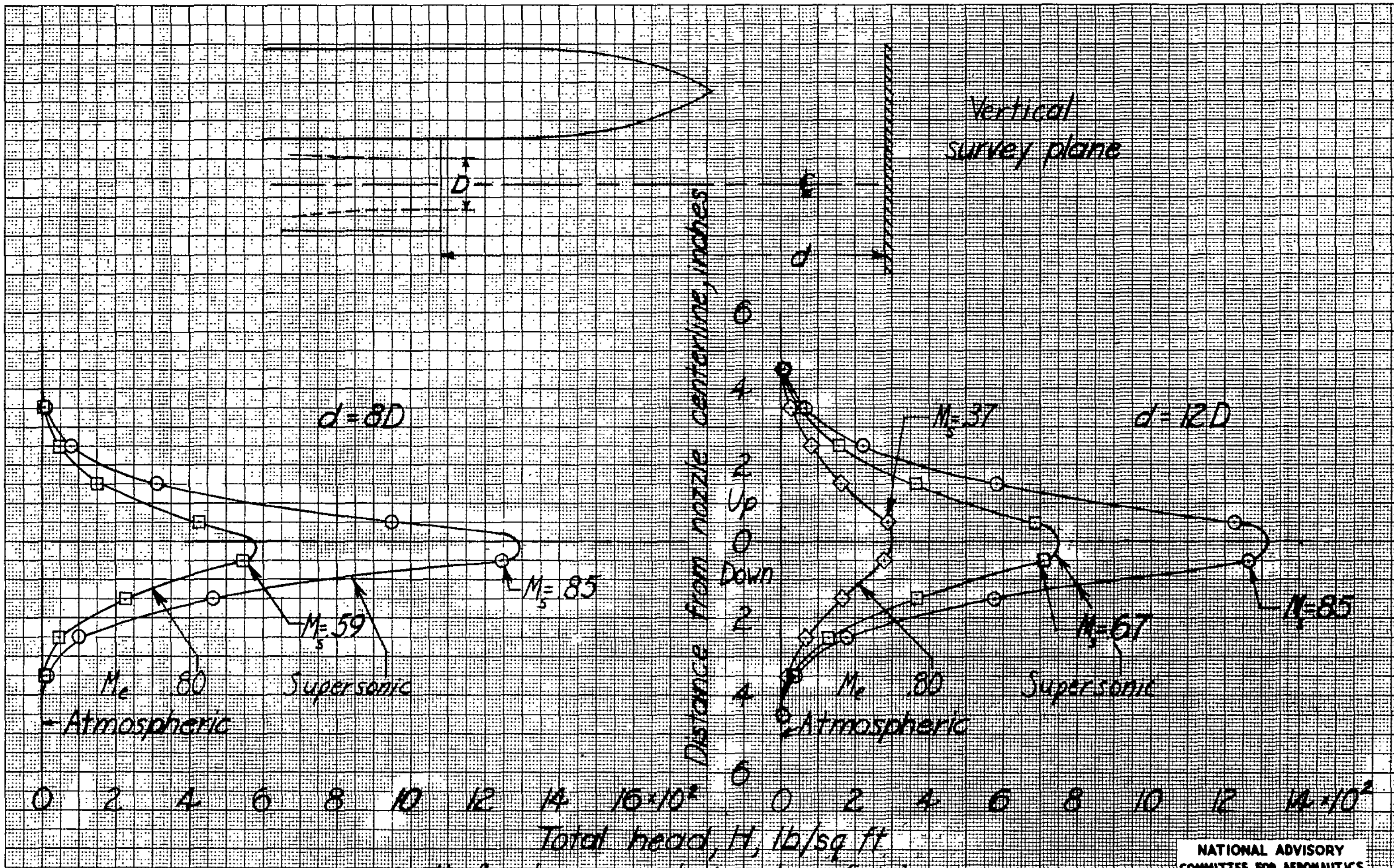


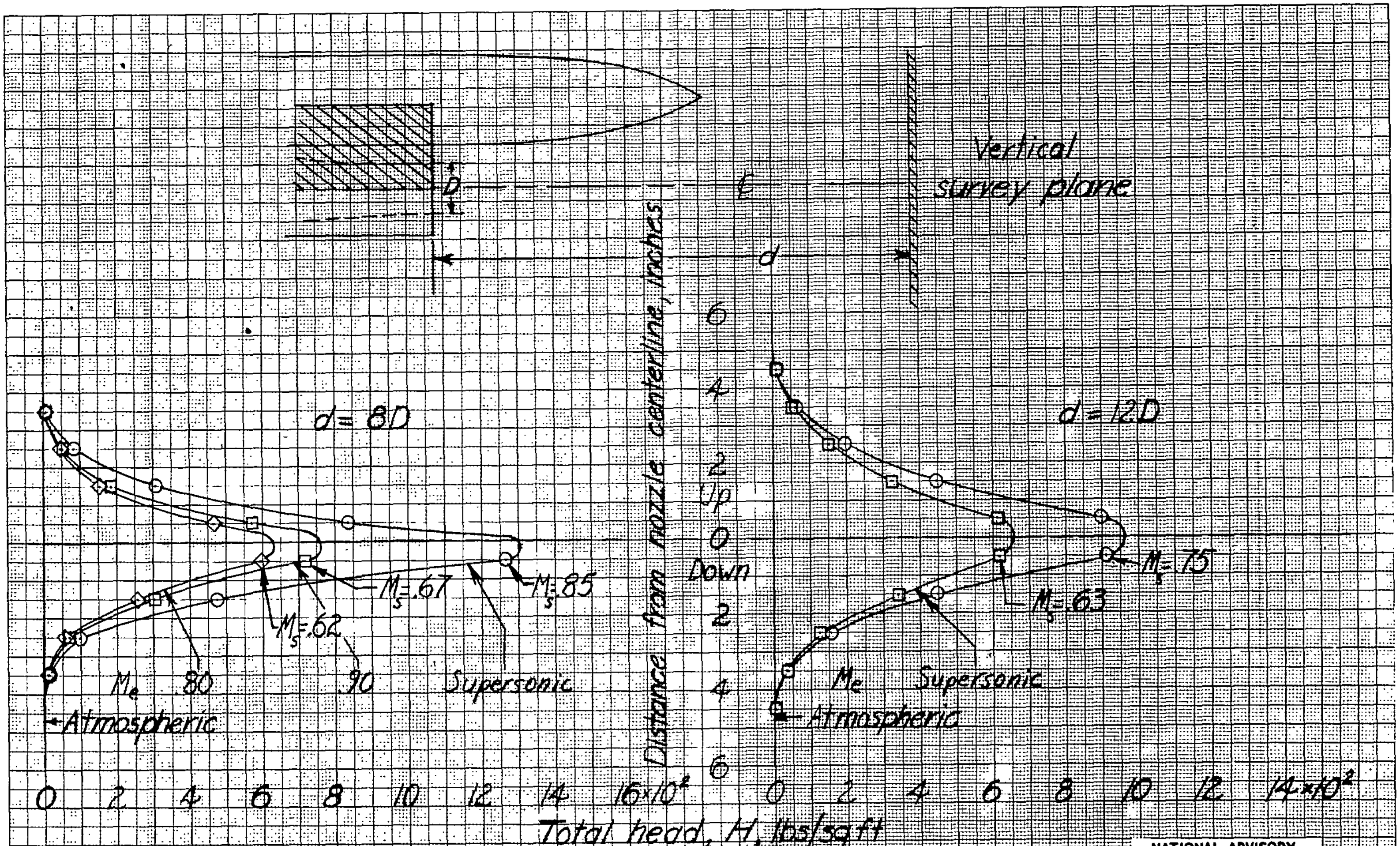
(c) Unsymmetrical nozzle exit

Figure 10.- Concluded



(a) No fuselage-nozzle juncture fairing

Figure 11 - Total head surveys for determination of effect of fuselage interference on jet inclination. Tests in still air.



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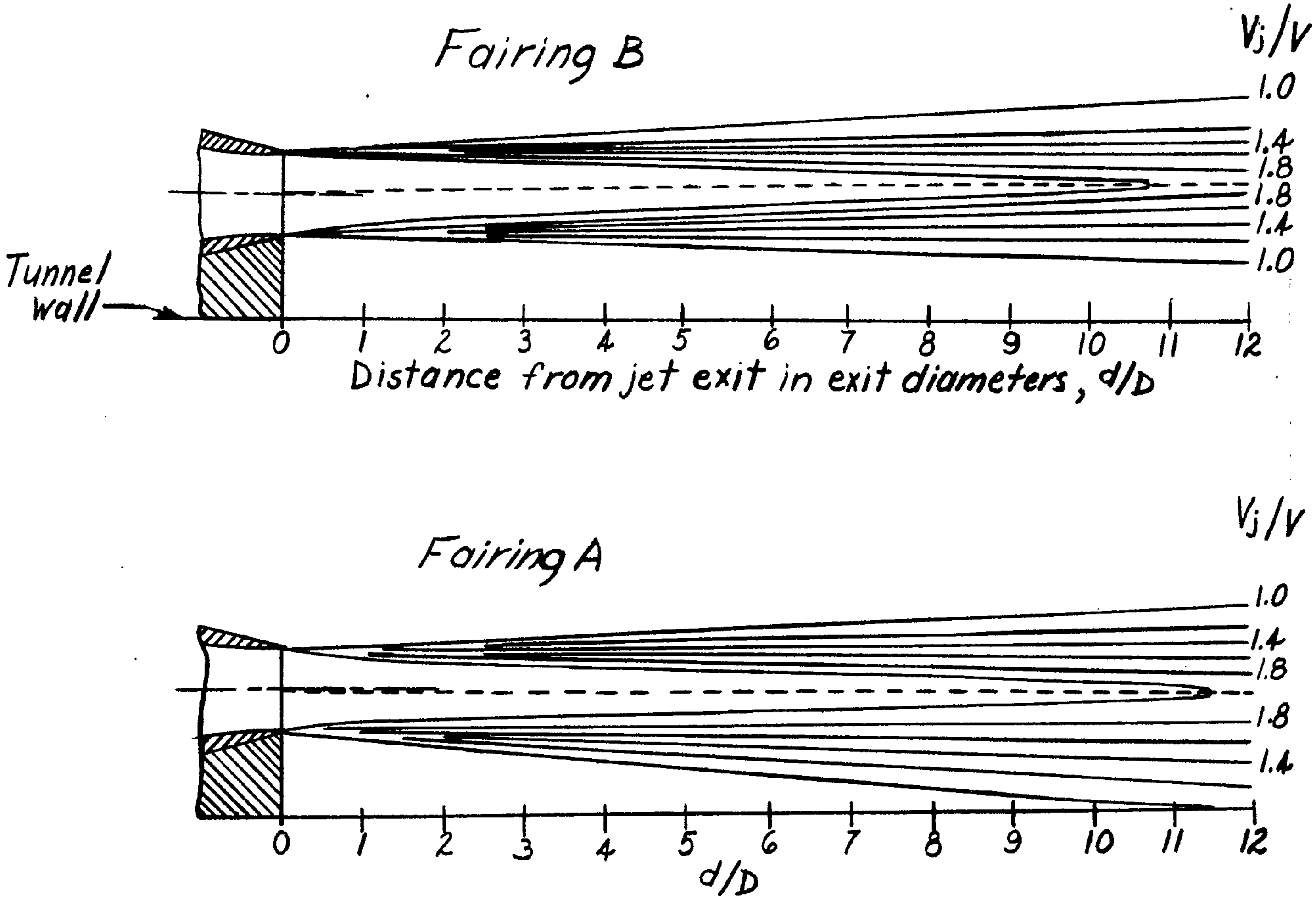
(b) Fuselage-nozzle juncture faired

Figure 11.- Concluded.



(a) Longitudinal velocity contours.

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Figure 12.- Velocity contours showing the effect of variation in fairing on jet deflection. Göttingen data obtained from reference 3.

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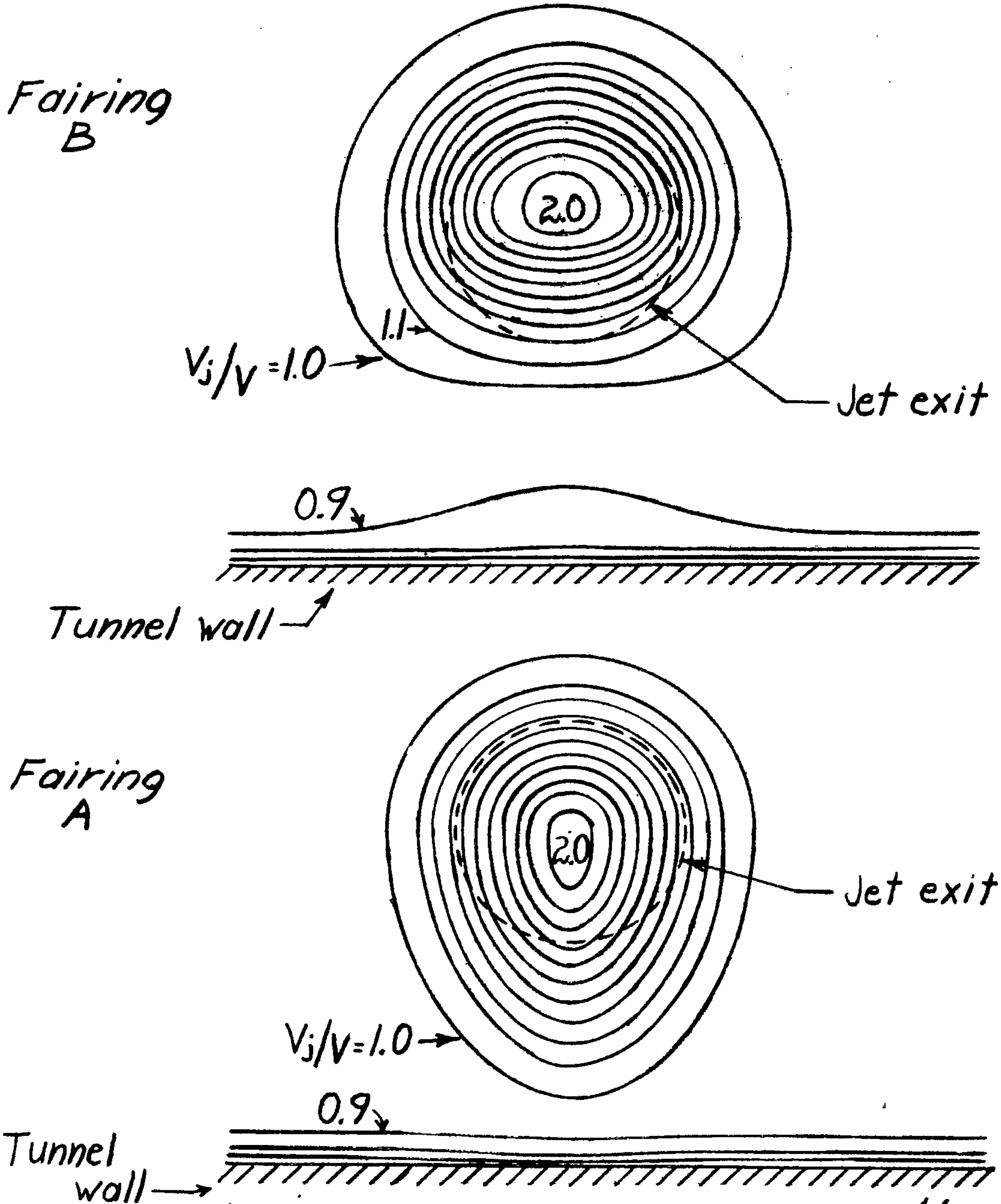

(b) Lateral velocity contours at $d/D = 8$.

Figure 12.- Concluded.

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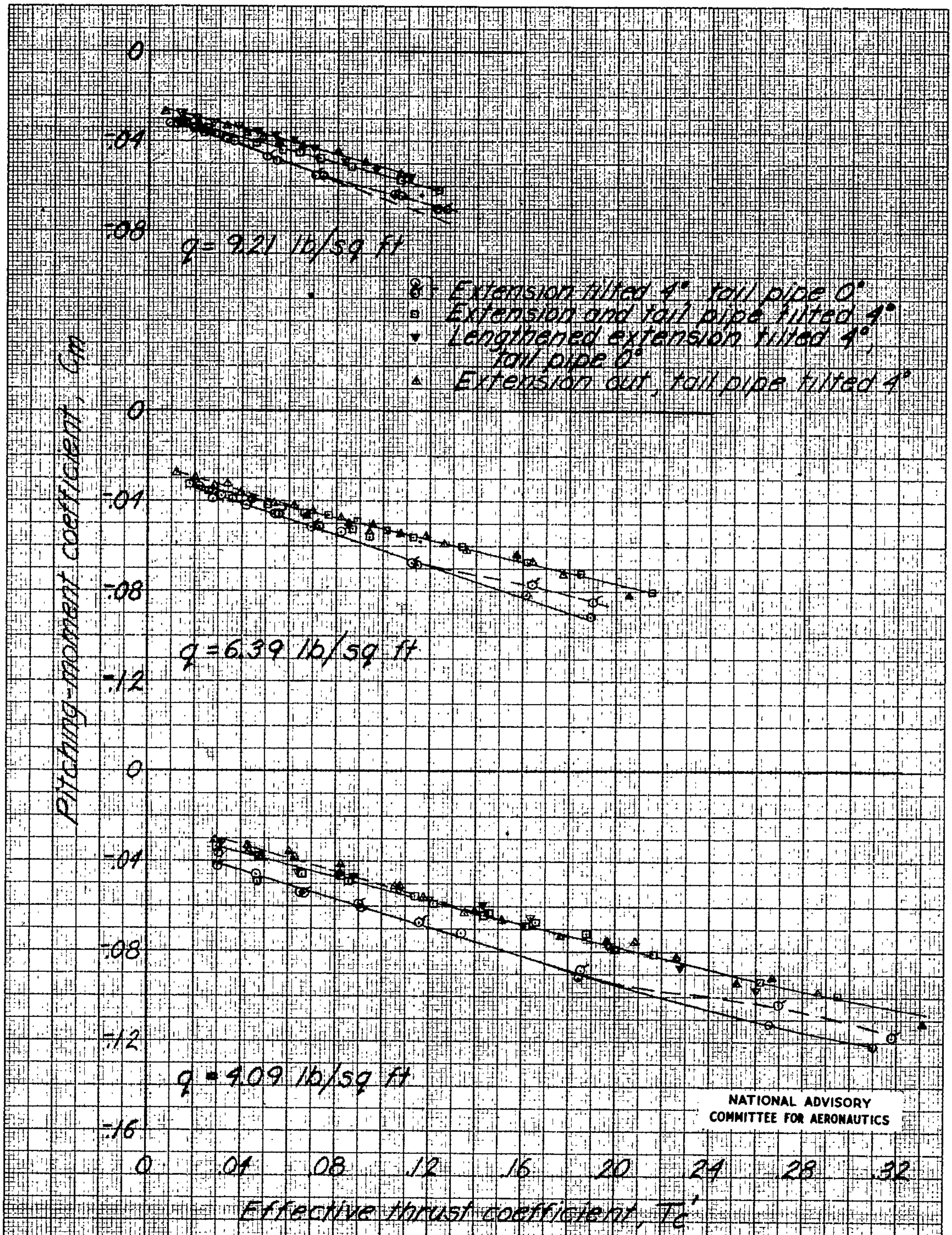

Figure 13-Variation of pitching-moment coefficient with effective thrust coefficient for various methods of tilting the jet on the complete model. $\alpha = 0°$, tail off. Wind-tunnel tests.

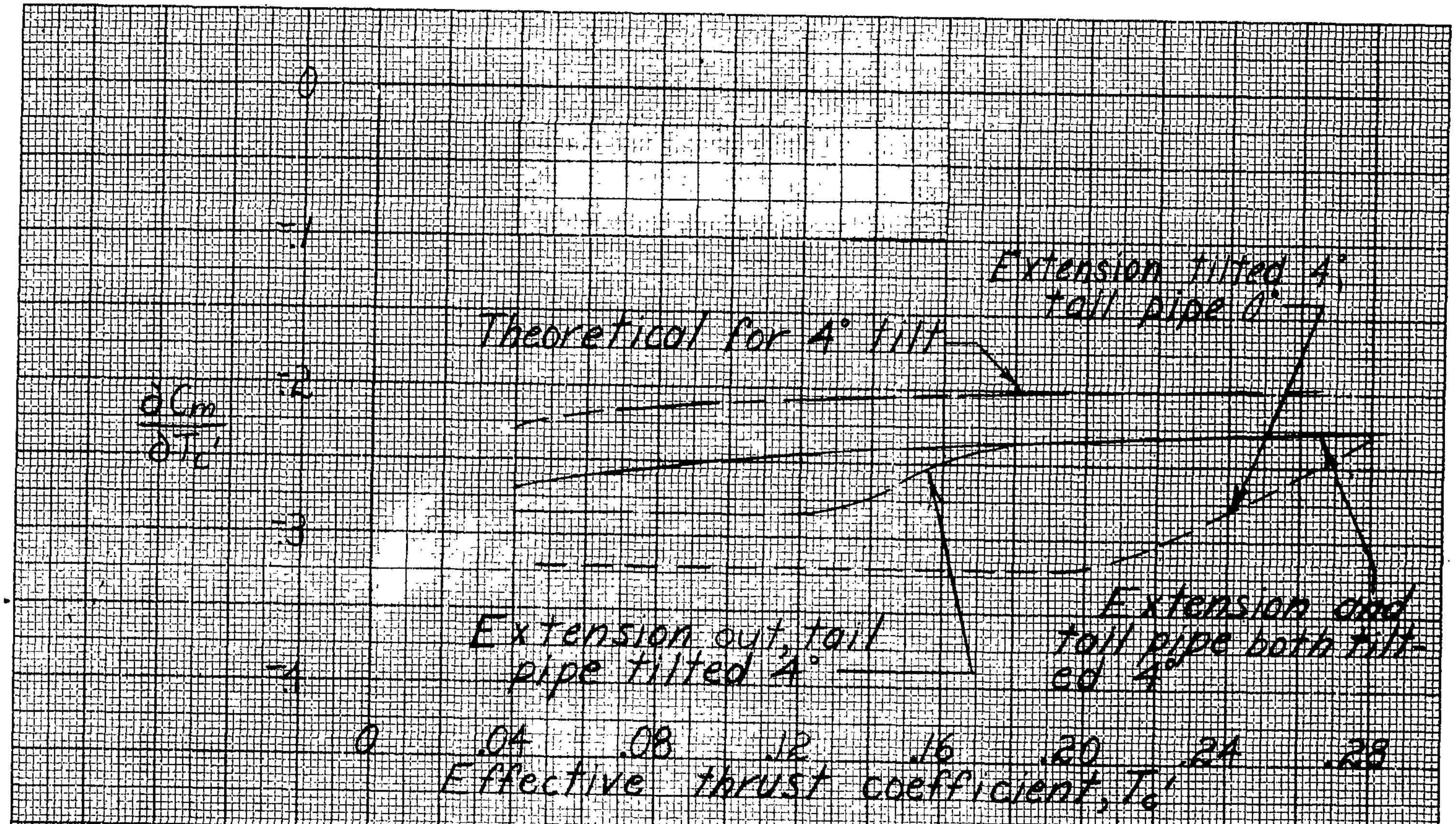

Figure 14.- Variation of the parameter, $\partial C_m/\partial T_c'$ with thrust coefficient for various methods used to tilt the jet. $q = 40.9$ lbs/sq ft, $\alpha = 0°$